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Mercury as a Heat Pipe Fluid

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by

J. E. Deverall

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ABSTRACT

Two heat pipes were tested to determine the feasibility of using mercury as a heat-pipe fluid: one pipe was life-tested for 10,000 h at 330°C to study the wetting characteristics of mercury in a stainless-steel structure; and the other was built and operated to determine the heat-transfer capability of a mercury system and to compare its operational limitations with theoretical values.

The life test indicates that good wetting of wick structures can be attained and that long-term operation is possible without excessive corrosion. The heat-transfer test demonstrated that mercury behaves as a normal heat-pipe fluid with regard to its operational limitations and startup dynamics. Construction of mercury heat pipes for high heat-transfer rates appears to be feasible for operation between 200° and 400°C.

INTRODUCTION

The heat pipe is a high thermal-conductance device which transfers heat by two-phase fluid circulation.[1] The operating temperature range of a heat pipe is determined by the type of working fluid used; with the appropriate choice of fluid, heat pipes can be constructed to operate from below 0° to 2000°C.[2] However, there is one section of this range, from 200° to 400° C, for which some difficulty exists in obtaining a suitable fluid. The temperatures in this range are too high for water because the vapor pressure is excessive and presents containment problems, and they are too low for alkali metals because the vapor pressure is insufficient to sustain operation. A survey indicates that the properties of organic fluids are not suitable as working fluids except for low heat-transfer rates, e.g., thermal control, or for special heat-pipe applications.[3] The fluid which appears to have the greatest potential as a working medium for this temperature range is mercury. It is, however, quite corrosive and poses some difficulty in obtaining good wetting of the wick structure, which is essential for heat-pipe operation.

A heat pipe was constructed with mercury as the working fluid and life-tested for 10,000 h at 330°C to study the wetting characteristics of mercury in a stainless-steel structure. Another mercury heat pipe was built and operated to determine the heat-transfer capability of a mercury system and to compare its operational limitations (e.g., wicking limit, sonic limit, and entrainment limit) with theoretical limitations.[4] Mercury has suitable properties for use as a heat-pipe fluid and, if good wetting is obtained, can be used for high heat-transfer rates. In these tests, wetting was obtained by the additions of magnesium and titanium to the mercury. Magnesium is an oxygen getter which cleans the surface, promoting wetting, and the titanium acts as an inhibitor which reduces corrosion.

An extensive study of corrosion or mass-transfer effects was not planned in these tests. Readily available materials and not necessarily the most corrosion-resistant ones were used. However, the life-test heat pipe was sectioned and carefully examined to determine corrosion effects.

LIFE TEST

Heat-Pipe Construction

The heat pipe was a 12-in.-long by 3/4-in.-o.d. Type-347 stainless-steel tube with a 0.035-in.-thick wall, which contained a 100-mesh Type-304 stainless-steel screen wick structure. The screen, rolled into a cylinder of three layers, was inserted into the heat pipe and pressed against the wall by forcing a steel ball through the assembly. Closure of the pipe was made by welding an end cap into each end. A 1/4-in.-o.d. tube, welded into one end cap, provided a means for loading the working fluid into the pipe and sealing it under vacuum. Before assembly, all parts of the pipe were outgassed at 1000°C in a vacuum furnace.

Heat was supplied by a 1/8-in.-o.d. Calrod heater which was wound around the evaporator zone over a length of 2-1/4 in. Temperatures were measured by chromel-alumel thermocouples spot-welded along the length of the pipe as shown in Fig. 1.

After the heat pipe was assembled and leak-tested, it was loaded with 122 g of clean mercury injected into the pipe through the fill tube by a hypodermic. A magnesium wire weighing 0.010 g and a titanium wire weighing 0.005 g were then dropped into the pipe through the fill tube to promote wetting and to inhibit corrosion. The pipe was subsequently connected to a vacuum system and evacuated overnight to remove the noncondensable gases. The pipe was sealed, while still connected to the vacuum system, by flattening a section of the fill tube and burning it off with a Heliarc torch.

Before the Calrod heater and the thermocouples were attached, the pipe was wrapped with a tape heater over its full length and heated to 400°C for two days to wet in. During this period the pipe was tipped back and forth and rotated frequently to wet all parts of the inner surfaces. Radiographs taken after this wetting-in operation indicated that only partial wetting had been obtained. The pipe was therefore heated for another two days, at 500°C, which resulted in complete wetting as shown by radiographs. The radiographs also showed that the surfaces, once wet, would rewet by raising one end of the pipe well above the wicking-limit height, allowing the mercury to drain out of the wick structure at that end. When the opposite end of the pipe was elevated, the drained section would readily rewet. Further evidence that good wetting had been achieved was demonstrated by operating the heat pipe and performing a wicking-height test. In this test, the evaporator end of the pipe is gradually elevated until the vertical height to which the wick structure can raise the liquid is exceeded. When this occurs, the wick in the evaporator dries out and the temperature rises rapidly, as indicated by a thermocouple at the end of the pipe. The measured wicking height was in close agreement with the calculated value, based upon screen pore size,

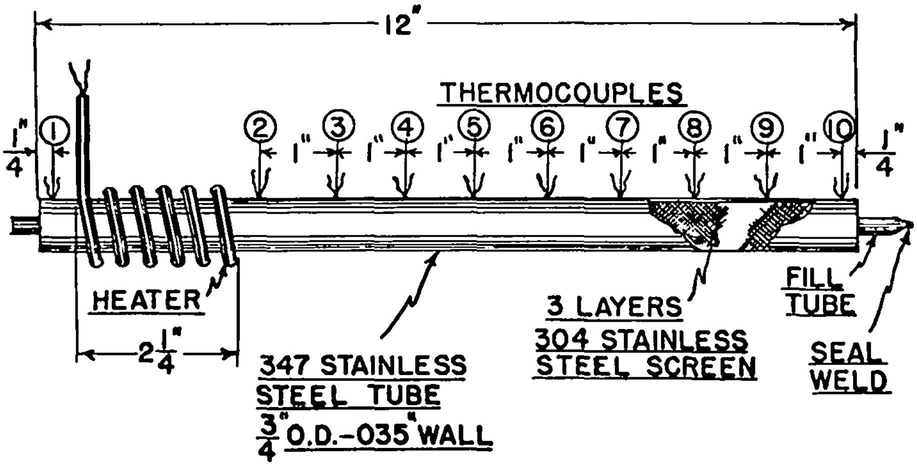

Fig. 1. Life-test heat pipe.

indicating that good wetting had been obtained and that the magnesium and titanium addition did not lower the surface tension of the mercury to any appreciable extent.

Heat-Pipe Operation

The heat pipe was placed in a well-ventilated hood (as a safety precaution in the event of leakage) and was operated in a horizontal position for 10,000 h at 330°C with a heater input of $\sim$ 100 W. At the start of the test, pipe operation was essentially isothermal over the entire length. Temperature measurements were taken at frequent intervals during the test to determine if any changes in operational characteristics occurred as indicated by the development of axial temperature gradients. Wicking-height tests were also performed periodically to ascertain whether there was any change in wetting conditions.

Postmortem Investigation

At the conclusion of the test, heat-pipe operation was still essentially isothermal. A final wicking-height test was made, and the heater and the thermocouples were then removed from the pipe. Radiographs were taken in both the horizontal and the vertical position to study the wetting conditions before the mercury was removed from the pipe. This was done by cutting off the fill tube and allowing the mercury to drain out. The mercury that had been trapped in the wick structure and had been retained on the wetted surfaces was removed by vacuum distillation at 400°C. The pipe was sectioned, and various parts were mounted and polished for photomicrographs and for microprobe examinations. Some sections of the tube and screen, along with the mercury which had been drained out, were analyzed spectrochemically. There was a small section of the screen in the evaporator zone on which a deposit of material had collected. Part of this deposit was examined photomicrographically, and the rest was analyzed spectrochemically.

Results

When the heat pipe was sectioned, the wick structure and the tube wall appeared to be in good condition. However, microscopic examination and chemical analysis showed that some corrosion and mass transfer had occurred. As shown in Fig. 2, practically all the screen wires were covered with a coating which appeared quite uniform throughout the structure and had an average thickness of 0.25 mils. Samples from the evaporator and condenser ends were quite similar. This coating also appeared on the tube wall and averaged about 0.6 mils. Spectrochemical and microprobe analyses of the coating on the wires revealed it to be an iron-nickel-chromium alloy similar to the original Type-304 stainless steel except that the manganese and chromium concentrations were lower and that the coating contained 10 to 100 ppm titanium. The coating on the tube wall was predominantly iron with less chromium and nickel than in the original Type-347 stainless steel. The coatings were very tenacious and appeared to form a protective layer due to the presence of titanium, which acted as an inhibitor. The wires were reduced in diameter by $\sim$ 0.7 mils. Changes in tube-wall thickness were negligible. The major corrosion effect occurred at the crossover points of the screen wires and was evidently a stress corrosion resulting from the compression of the screen against the tube wall when the ball was forced through the structure. Where the wires crossed, large pressures were exerted on the metal causing permanent strain and sites for stress corrosion. A typical example of this corrosion is shown in Fig. 3. No other appreciable sign of corrosion was detected on the wires except at these points. Neither was there any evidence of this type of corrosion in the container-wall material.

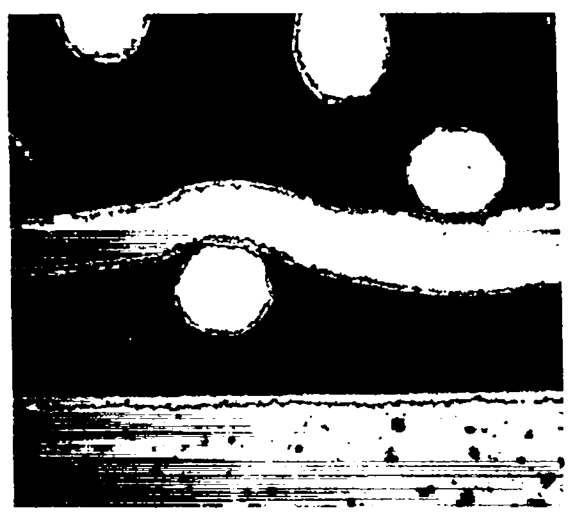

Fig. 2. Coatings on screen wires and tube wall.

Fig. 3. Stress corrosion at wire intersections.

Radiographs taken after the test showed an accumulation of material had formed in a small section of the evaporator, on the inner layer of the wick cylinder. This accumulation was about 1-in. long by 1/4-in. wide and 1/16-in. deep, and was well bonded to the screen. It had a crystalline structure, was quite porous, and did not penetrate into the other two layers of the screen to any appreciable extent, as shown in Fig. 4. Chemical and microprobe analyses showed that the deposit was a mixture of nickel, chromium, manganese, and iron, with traces of magnesium, mercury, and molybdenum. The mixture consisted primarily of nickel, was high in manganese, low in iron and chromium content, and had a distribution of elements completely different from that of the original stainless steels. The presence of titanium was not detectable. This deposit indicated that some mass transfer had taken place. Each of the constituents apparently had some solubility in mercury and was carried to the evaporator section where it was deposited when the mercury was vaporized. Both size and porosity of the deposit appeared to be such that heat-pipe operation would not be affected.

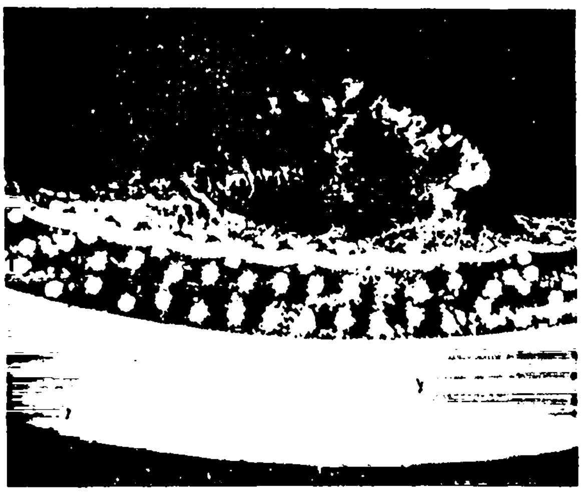

Fig. 4. Deposit in evaporator.

When the mercury was drained out of the heat pipe, it was accompanied by a small amount of loose, black material. Chemical analysis indicated that this material was primarily magnesium and mercury, with traces of iron and nickel. The magnesium was probably either in the form of MgO from the gettering process or was pure excess magnesium which did not combine. The mercury appeared to be trapped in the voids of the magnesium structure. A small amount of this black material will form when additives are used to promote wetting but it should not affect heat-pipe operation. Chemical analysis of the mercury which was drained out of the pipe showed that it was identical to the original mercury used for loading, with no additional magnesium or titanium in solution.

HEAT-TRANSFER CAPABILITY TEST

Heat-Pipe Construction

This heat pipe was a Type-347 stainless-steel tube with a length of 19-5/8 in., an o.d. of 0.600 in., and an i.d. of 0.495 in. The wick structure consisted of three layers of 100-mesh, Type-304 stainless-steel screen pressed against the wall by forcing a steel ball through the pipe. Closure of the heat pipe was made by welding end caps into each end, with a 1/4-in.-o.d. tube in one cap which was connected to a bellows valve for loading and sealing the pipe. All parts were outgassed at 1000°C before assembly.

Heat was supplied by a helical Nichrome wire enclosed in insulator beads and wound around the evaporator over a length of 7 in. This winding was surrounded by a 2-in.-diam tube, filled with insulation, and sealed at the ends with Alundum cement. Three thermocouples were attached to the heater winding to monitor heater temperature, and seven thermocouples were spot-welded along the length of the pipe as shown in Fig. 5 to indicate heat-pipe temperatures. Heat was rejected to a water-cooled gas-gap calorimeter fitted with a ΔT meter across the inlet and outlet connections to provide heat-balance measurements. The gas gap was fitted with a fine capillary tube so that helium could be fed into the gap to replace the air, increasing the thermal conductivity and increasing the heat rejection rate by a factor of four.

After the heat pipe was assembled, it was loaded with 177 g of mercury with magnesium and titanium additions, was evacuated, and finally sealed by closing the valve. The assembly was then disconnected from the vacuum system, and the pipe was wet-in at 500°C for two days using a tape heater wrapped around the full length of the pipe. Radiographs were taken, and a wicking-height test was performed with a temporary heater to ensure adequate wetting had occurred. The pipe was then fitted with the heater, thermocouples, and calorimeter, and was placed in a metal box filled with vermiculite insulation. After the wetting-in process, it was noted that there was still some noncondensable gas in the pipe. This was not removed until after the first three runs were made to determine the effect of the gas on heat-pipe operation. As a safety precaution, the heat pipe was operated in a well-ventilated hood.

Test Procedure

The heat-transfer test of this pipe consisted of six runs under different operating conditions to demonstrate the major limitations and heat-transfer capability of a heat pipe with mercury as the working fluid.

Run 1 -- Heater end elevated.
Air in calorimeter gap.
Noncondensable gas in pipe.

Run 2 -- Heater end elevated.
Helium in calorimeter gap.
Noncondensable gas in pipe.

Run 3 -- Condenser end elevated.
Helium in calorimeter gap.
Noncondensable gas in pipe.

Run 4 -- Condenser end elevated.
Helium in calorimeter gap.
Pipe vented--noncondensable gas removed.

Run 5 -- Condenser end elevated.
Air in calorimeter gap.
Noncondensable gas removed.

Run 6 -- Heater end elevated.
Noncondensable gas removed.
Calorimeter removed.
Heat rejection by natural convection.
Constant power -- 300 W.

For Runs 1 through 5, the pipe was placed in the proper position, with air or helium in the calorimeter gap, and the cooling water flow rate adjusted. The heater was then turned on and the pipe gradually heated to various temperature levels until the maximum temperature was reached. At each level, temperature equilibrium was established before

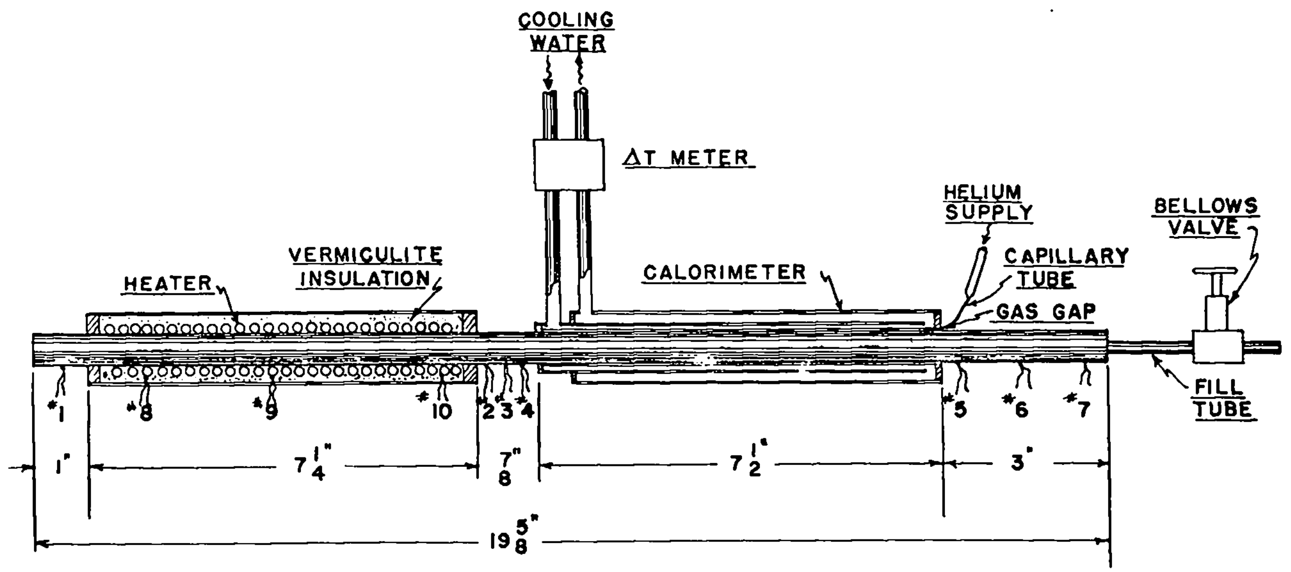

Fig. 5. Heat-transfer-capability heat pipe.

taking readings and proceeding to the next level. Temperatures were measured and recorded on a 16-point recorder, and temperature differences of the ΔT meter across the calorimeter inlet and outlet connections were measured in millivolts by a potentiometer. The flow rate of water was determined by timing with a stopwatch the filling of a container of known volume. The electrical input to the heater was taken as the product of voltage and current, as measured by meters. Heat-transfer rates for the pipe, however, were taken as the values calculated from the calorimeter data which were considered more accurate than the power-input measurements. When measurements were completed at the highest temperature level, the power was shut off and the pipe was allowed to cool to room temperature. The next set of operating conditions was then established and the test procedure repeated. A plot of temperature versus heat-pipe length, at various heat transfer rates, was made for each run to show startup and operating characteristics.

For Run 6, the calorimeter was removed so that a low heat-rejection rate would be obtained by natural convection cooling. Three thermocouples were added, and the thermocouple spacing was rearranged to provide a more accurate picture of the temperature profiles. Liquid return to the evaporator was by capillary action as the heater end was elevated 1-1/2 in. With the pipe at room temperature, a constant power input was applied to the heater, and the temperatures were recorded during the startup.

Results

Run 1

The wicking limit was demonstrated in this run by elevating the heater end so that liquid return to the evaporator was by capillary action of the wick structure. When the heat-transfer rate exceeded 700 W, the wick structure was not capable of supplying sufficient liquid to the evaporator due to inadequate capillary pumping force, and the pipe became wick-limited. The wick structure began to dry out and overheat as indicated by Thermocouple 1 (Fig. 6). After startup, the temperature became essentially isothermal over the length of the pipe because the heat-rejection rate to the calorimeter was relatively low with air in the gap. This low

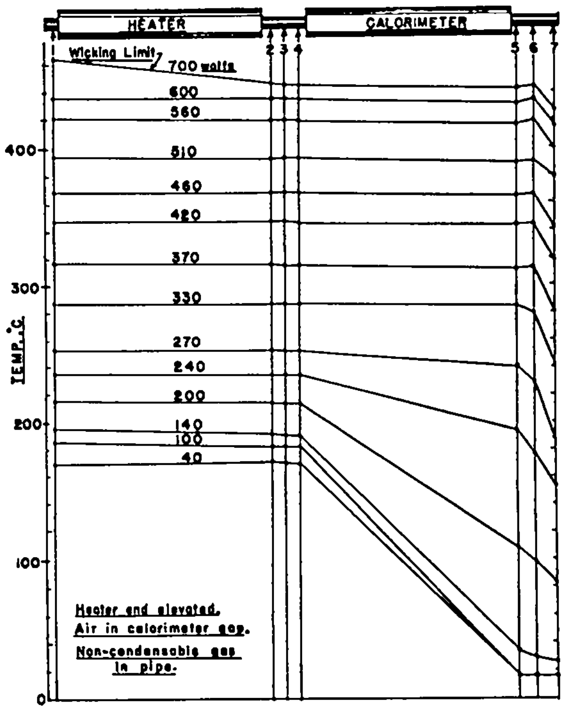

Fig. 6. Heat-transfer test, Run 1.

rejection rate also resulted in a fairly high operating temperature level for a given heat-transfer rate. There was an appreciable temperature drop over a small section of the pipe at the condenser end due to a pocket of noncondensable gas. The pocket was compressed to a smaller volume at higher temperatures, which resulted in a decrease of this temperature drop.

Run 2

This run was also made with the heater end elevated and demonstrated the wicking limit as shown in Fig. 7. The limit occurred at approximately the same heat-transfer rate as in Run 1, but the operating temperature level was lower because the heat-rejection rate in Run 2 was much higher with helium in the calorimeter gap. This high rejection rate also resulted in an appreciable temperature gradient along the calorimeter section. This temperature gradient increased because the vapor flow decreased when the wicking limit was exceeded. Although the evaporator temperature increased, the amount of vapor formed was less because of the drying out of the wick structure. The temperature drop at the end of the pipe was still present due to the pocket of noncondensable gas.

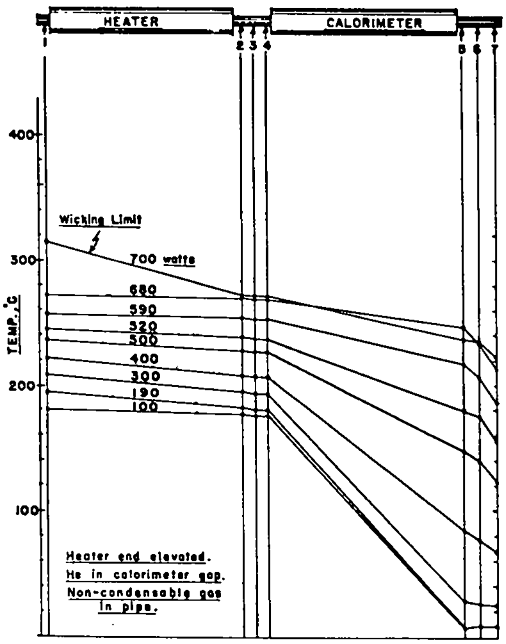

Fig. 7. Heat-transfer test, Run 2.

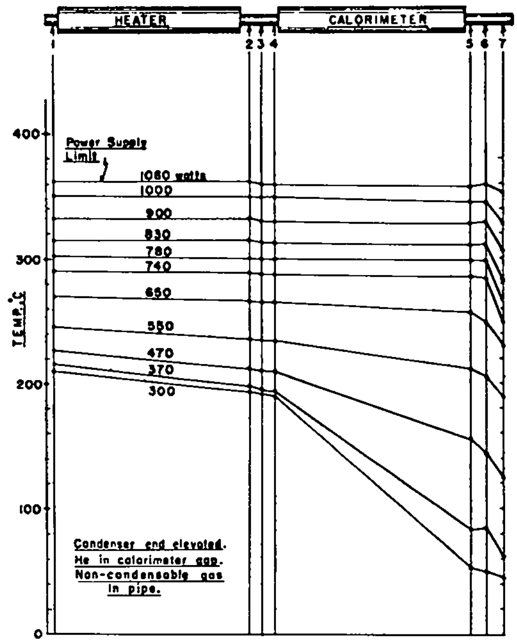

Fig. 8. Heat-transfer test, Run 3.

Run 3

To eliminate the wicking limitation and to investigate other limitations associated with the vapor passage, the pipe was operated with the condenser end elevated. Elevating the end provided a gravity return for the liquid, and pipe operation consequently did not depend upon the capillary pumping force of the wick structure. This permitted the study of limitations resulting from the dynamics of vapor flow. The calorimeter was filled with helium to provide the maximum heat-rejection rate, and the pipe operated to the maximum output of the power supply. No heat-pipe limitation was observed up to a heat-transfer rate of 1060 W, and the pipe operated isothermally within 5°C over its length except for a short section at the end due to the noncondensable gas pocket (Fig. 8). At the highest power level there was evidence of a slight temperature recovery to within 2°C of the evaporator temperature.

Run 4

The presence of noncondensable gases in a heat pipe not only affects the temperature gradient along the pipe, it can also have considerable influence upon the start-up dynamics. To study other limitations with mercury as a working fluid, the pipe was reevacuated to remove the noncondensable gases present. In this run, the condenser end was elevated to eliminate the wicking limitation and helium was injected into the calorimeter gap to provide maximum heat rejection. As shown in Fig. 9, it was not possible to raise the temperature of the condenser section of the pipe by increasing the power input. The high heat-rejection rate resulted in low evaporator exit temperatures with correspondingly low vapor density and, consequently, sonic vapor velocities. This is the sonic limit of a heat pipe which results in choked vapor flow and limited heat transfer to the condenser section. In this run, the high velocities eventually swept liquid out of the evaporator wick structure, causing it to dry out and overheat. This sweeping of liquid out of the wick is the entrainment limit and is a function of the ratio of inertial vapor forces and liquid-surface tension forces known as the Weber number, $\frac{\rho V \lambda}{\delta}$, where ρ is the vapor density, V the vapor velocity, λ a characteristic length dependent upon the wick structure, and δ the liquid surface tension. When this ratio becomes greater than one, the inertial forces predominate and liquid droplets are swept out of the wick structure. It is often possible to hear the droplets impinge on the condenser end when this limit occurs. Under these

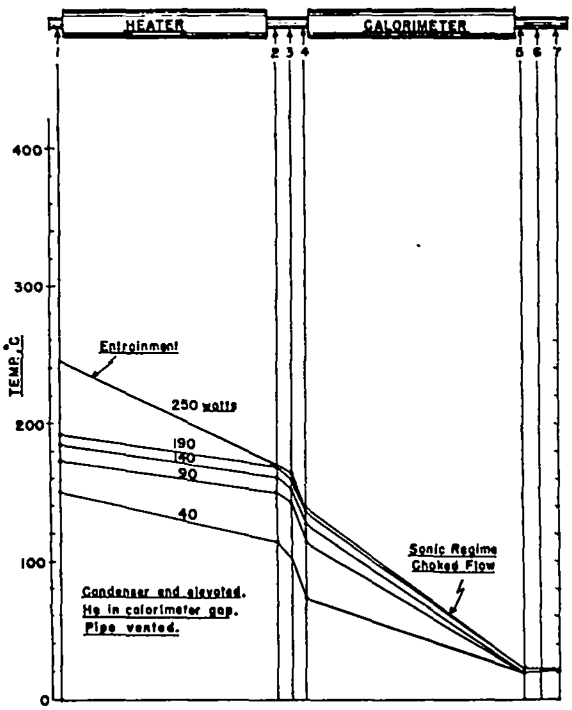

Fig. 9. Heat-transfer test, Run 4.

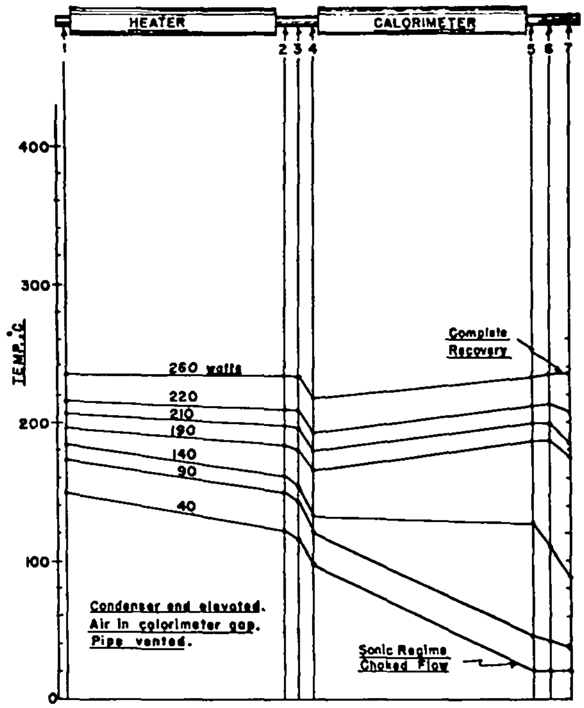

Fig. 10. Heat-transfer test, Run 5.

conditions, the heat pipe will not start up. This did not occur when the noncondensable gas was present because the gas tended to retard the vapor flow and, in effect, shortened the length of the condenser section. This reduced the heat-rejection rate,enabling the pipe to move out of the sonic flow regime and gradually come up to temperature.

Run 5

Another run was made under the same conditions as Run 4 except that the heat-rejection rate was reduced by having air in the calorimeter gap. With air in the gap, the pipe would start up even though it was initially operating in the sonic regime as shown in Fig. 10. The heat-rejection rate in this case was low enough for the evaporator exit to gradually heat up, enabling the pipe to move through the sonic-limit regime and come up to temperature. No operating limit was reached,and almost complete temperature recovery was obtained at the condenser end. The pipe could have been operated at much higher heat-transfer rates once it was up to temperature by gradually increasing the power input and substituting helium in the calorimeter gap.

Run 6

In this run, a transient-state startup was made to observe the temperature recovery in a mercury heat pipe during startup from room temperature at a constant power input of 300 W to the evaporator. The temperature gradients, as a function of time, are shown in Fig. 11. Although the vapor velocity was supersonic and choked vapor flow existed at the beginning of the startup, the pipe passed through this regime and reached an isothermal operating level. This occurred because the heat-rejection rate was very low and, even with choked flow, sufficient vapor reached the end of the pipe to start temperature recovery at a relatively low temperature. Under these conditions the pipe was able to rise in temperature, with an increase in vapor density and a subsequent decrease in vapor velocity, before entrainment could cause failure. At this power input and heat-rejection rate, no operational limitations were encountered.

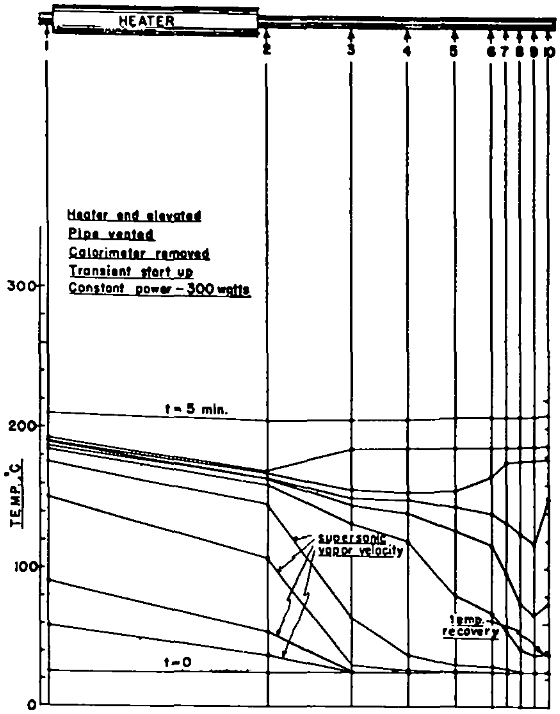

Fig. 11. Heat-transfer test, Run 6.

DISCUSSION

Life Test

The results of the life test indicated that, at the temperature and heat-transfer conditions under which the pipe operated, no catastrophic corrosion occurred in 10,000 h. Based upon the most corrosive effect, which occurred at the intersection of screen wires, and assuming that this corrosion was continuous and of a uniform rate, a life expectancy of at least four years may be anticipated. If most of the stress corrosion occurred at the beginning of the test and then diminished as the stress points disappeared, the life expectancy would be even longer.

The materials used for construction of the heat pipe were not necessarily the most corrosion-resistant to mercury. Several low-carbon steels and ferrous metals, tested in dynamic mercury loops, have been reported to be more corrosion-resistant to mercury than Type 304 or 347 stainless steels. It would also be better to use one type of material for both the container and the wick structure to eliminate any electrolytic effect. Regardless of which materials are used, however, the wick structure should be annealed after assembly to stress-relieve any areas that were compressed during fabrication. This should reduce the possibility of stress corrosion such as that encountered in this test.

The mass transfer which occurred in this test did not appear to have any noticeable effect upon heat-pipe operation and did not reduce the wick structure to any appreciable extent. The heat-transfer rate, however, was only 100 W; at higher rates, mass transfer may become a factor. It is possible that once the coating is formed by the titanium reaction, this mass transfer would be reduced or become negligible. In any event, more testing of mass-transfer effects should be made with different materials, at different temperatures, and with much higher heat-transfer rates.

The wetting attained in this type of wick structure was excellent by using magnesium and titanium additions. This method has been used for many years in mercury boiler systems and has been quite successful. In heat pipes, however, the problem is much more difficult because of the wick structure. Wetting must penetrate into all the pores to have an effective capillary pumping force. In this test, the pipe had to be heated to 500°C for complete wetting because at 400°C only partial wetting was obtained. The high surface tension of mercury makes the penetration into small pores difficult and, for very fine pore structures, it may be necessary to use a combination of temperature and pressure to obtain wetting, as discussed in the heat-transfer capability section below.

Based upon the results of this single life test, it appears that mercury is a suitable heat-pipe fluid from the standpoint of wettability and corrosion. The system used in the test could be applied to many heat-transfer problems, and, with further development work, it should be possible to build pipes for very high heat-transfer rates. Mercury has a very high surface tension which can produce large capillary pumping forces, and, although this is somewhat offset by its high density in a gravity field, it should be an excellent working fluid for space applications.[5,6]

Heat-Transfer Capability Test

The results of this test indicate that mercury behaves as a typical heat-pipe fluid if good wetting of the wick structure is obtained. The wick structure used in this test, consisting of three layers of 100-mesh screen, was readily wet by the mercury at 500°C when magnesium and titanium additions were used. The wicking-height test of this pipe showed that good wetting had been achieved because the capillary forces were capable of wicking the mercury to a vertical height of 6 in. This is about 50% higher than the value calculated on the basis of screen-pore size, which indicates that there was a considerable amount of compression and intermeshing of the screen when the steel ball was forced through the structure. This resulted in a much smaller effective-pore size and, consequently, in a higher capillary pumping force. For this type of wick structure, however, the compression also increased the liquid-flow resistance and resulted in a wicking limit of 700 W.

A second heat-transfer capability pipe with a composite wick, consisting of a fine capillary cylinder forming an annular liquid-flow path, could not be wet-in just by additives. The capillary structure in this case consisted of eight layers of 400-mesh screen wrapped on a copper mandrel, inserted into an outer copper tube, and drawn down through a die. The copper was then etched away with nitric acid leaving the fine-pore cylinder. This gave a highly compressed structure with a pore size of $\sim 20\ \mu$. Several attempts were made to wet-in this structure, but radiographs showed that only partial wetting was obtained because the high surface tension of the mercury prevented its penetration into the structure; the pipe therefore could not be used for heat-transfer tests. Some other method must be devised to wet-in wick structures with very small pores for use in pipes with high heat-transfer rates. One method that has been employed to achieve wetting of surfaces by mercury without the use of additives is copper plating. The surfaces are well deoxidized by the plating process and kept in this condition by the copper coating. When in contact with mercury, the copper is dissolved and the mercury is able to wet the clean surface underneath. It is doubtful, however, if this method would be any improvement over the use of additives because of the difficulty in plating the inner surfaces of the wick structure. One possible solution may be to fill the heat pipe completely with liquid mercury and to apply a high pressure to the pipe at 500°C to force the liquid into the fine pore structure. The excess mercury could then be drained out, leaving only the amount required to saturate the wick structure.

The need for a composite wick structure in high-heat-transfer applications was demonstrated in Runs 1, 2, and 4. Limitations of wicking and entrainment can be overcome to a great extent by the use of the composite wick. It produces a high capillary pumping force and a low-resistance flow path which minimizes the wicking limitation. The small-pore capillary also greatly reduces the possibility of entrainment failure because the λ term of the Weber Number is much smaller and reduces the ratio of inertial-to-surface tension forces below unity at sonic velocities. If these two limitations are effectively reduced, the maximum heat-transfer rate is then controlled primarily by the sonic limit, at least in the lower section of the operating temperature range. As shown in Table I, high heat-transfer rates can be obtained up to this limit. The sonic limit is the maximum axial heat-transfer rate that can be attained at a given evaporator temperature because of choked vapor flow, and is independent of the heat-rejection rate. The other major operational limit of heat pipes that can be a factor is boiling in the wick at the heat-input section, but this is seldom encountered in liquid-metal heat pipes.

The start-up dynamics of this mercury heat pipe were in accordance with predicted theory for the various operating conditions.[7] The presence of a noncondensable gas in the pipe aided in startup as demonstrated in Runs 1, 2, and 3. The gas automatically controlled the heat-rejection area so that the pipe could come up to temperature before the entrainment failure-mode occurred. The same effect was achieved, when the gas was not present, by reducing the heat-rejection rate. In Run 5 this was done by having air in the calorimeter gap, and in Run 6 by using only convective cooling. The transient state startup in Run 6 gave a good example of the temperature recovery which occurs in heat pipes.

The properties of mercury (e.g., vapor pressure, surface tension, vapor density, viscosity, and latent heat of vaporization) make it a suitable fluid for use in heat pipes operating above 200°C

TABLE I. Sonic Limit for Mercury				
T_1, Evap. Entrance, °C	Vapor Pressure at T_1, mm Hg	T_2,* Evap. Exit, °C	Axial ΔT Along Evap., °C	Max. Axial Heat Transfer, W/cm^2
150	3.3	117	23	54
160	4.8	136	24	79
170	6.9	145	25	113
180	9.8	153	27	158
190	13.7	162	28	219
200	18.9	171	29	298
210	25.8	180	30	402
220	34.7	188	32	534
230	46.0	197	33	702
240	60.5	206	34	913
250	78.7	215	35	1174
260	101.4	223	37	1497
270	129.4	232	38	1891
280	163.5	241	39	2368
290	205.0	249	41	2941
300	255.0	258	42	3625
310	315.0	267	43	4435
320	386.0	275	45	5388
330	471.0	283	47	6503
340	567.0	292	48	7799
350	684.0	300	50	9299
360	818.0	309	51	11023
370	972.0	318	52	12996
380	1152.0	327	53	15244
390	1352.0	334	56	17792
400	1585.0	342	58	20668

*Static vapor pressure at evaporator exit.

$$P_2 = \frac{P_1}{1+M^2k},$$

where:
M = Mach No. = 1 at sonic flow; and
k = ratio of specific heats = 1.667.

$$P_2 = \frac{P_1}{2.667}$$

T_2 = Saturation temperature corresponding to the static vapor pressure P_2.

as shown in Fig. 12. Its operational characteristics as a working fluid compare favorably with those of other liquid metals. Although there are still some problems to be solved with regard to the wetting-in of fine-pore wick structures, the mercury heat pipe has excellent heat-transfer capability and appears to be the most promising system for the temperature range from 200° to 400°C.

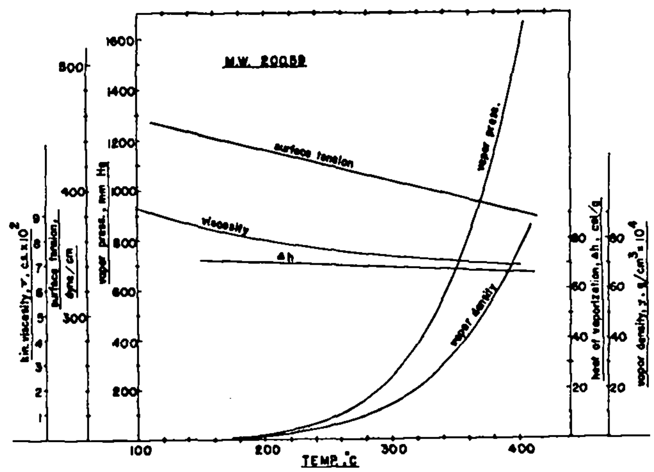

Fig. 12. Properties of mercury.

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